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14. ABSTRACT
This report decribes the research and results of the activity on various projects over the period of the grant. The optics of study include atom optics and matter-wave quantum point contacts, theory of optical refrigeration of semiconductors and nonlinear optical response of quantum well Bragg structures, tuneable high-brightness vertical external cavity surface emitting lasers and generation of blue-green lasers by frequency doubling, quantum dots for cavity QED entanglement, near-field nonlinear optics, and optically bound matter. The project supports student

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Report Title

Research in the Optical Sciences

ABSTRACT

This report decribes the research and results of the activity on various projects over the period of the grant. The optics of study include atom optics and matter-wave quantum point contacts, theory of optical refrigeration of semiconductors and nonlinear optical response of quantum well Bragg structures, tuneable high-brightness vertical external cavity surface emitting lasers and generation of blue-green lasers by frequency doubling, quantum dots for cavity QED entanglement, near-field nonlinear optics, and optically bound matter. The project supports student research and generates opportunities for scientific publications. The projects involve interaction with colleagues and DOD laboratories and supports in-house Army and Air Force research efforts to develop optics technology relevant to military applications.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

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Number of Presentations: 0.00

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

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Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
Robert M. Leone	0.75
Jeffrey Weiss	0.93
FTE Equivalent:	**1.68**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Christopher M. Shanor	0.27
FTE Equivalent:	**0.27**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Rudolf Binder	0.22	No
Brian P. Anderson	0.35	No
FTE Equivalent:	**0.57**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment

Technology Transfer

COMPILED FINAL REPORTS – (August 1, 2010 – September 10, 2010)

Atom Optics and Matter-wave Quantum Point Contacts::
Experiments with highly oblate Bose-Einstein condensates
PI: Brian Anderson

(4) Statement of the problem studied.

A vortex dipole in a classical or quantum fluid consists of a pair of vortices of opposite circulation, with the dynamics of each vortex core dominated by interaction with the fluid flow pattern of the counterpart oppositely-charged vortex, as well as the boundary conditions in the fluid. Although single vortices carry angular momentum, vortex dipoles can be considered as basic topological structures that carry linear momentum in stratified or two dimensional fluids. Vortex dipoles are widespread in classical fluid flows, appearing for example in ocean currents and soap films, and have been described as the primary vortex structures in two-dimensional turbulent flows [1]. In superfluids, the role of vortex dipoles is less well established; however, vortices and antivortices are prevalent in superfluid turbulence, and are also significant in the Berezinskii-Kosterlitz-Thouless (BKT) transition [2], and in phase transition dynamics [3]. This prevalence across a broad set of systems and scenarios implies a quantitative study of vortex dipoles will contribute to a broader and deeper understanding of superfluid phenomena. The realization of vortex dipoles in dilute BECs is especially significant as BECs provide a clean testing ground for the microscopic physics of superfluid vortices [4].

(5) Summary of the most important results

Numerical simulations based on the Gross-Pitaevskii equation (GPE) have shown that vortex dipoles are nucleated when a superfluid moves past an impurity faster than a critical velocity, above which vortex shedding induces a drag force [5]. Vortex shedding is therefore believed to be a mechanism for the breakdown of superfluidity. Experimental studies of periodic stirring of a BEC with a laser beam have measured a critical velocity for the onset of heating and a drag force on superfluid flow [6]. These measurements were based on a sharp increase in the heating rate at a particular stirring velocity, and thus can be considered as macroscopic type measurements. Similarly, vortex phase singularities were observed in the wake of a moving laser beam in a subsequent experiment [7], a type of mesoscopic observation. However, a microscopic picture of vortex dipole formation and the ensuing dynamics has not been established experimentally, prior to the work described here. In our recent work, single vortex dipoles were deterministically nucleated by causing the highly oblate, harmonically trapped BEC to move past a repulsive barrier, while the BEC was held in the combined magnetic and optical trap. Our accomplishments include: (i) measuring a critical velocity for vortex dipole shedding, and finding good agreement with numerical simulations and earlier theory [8]; (ii) discovering that the nucleation process exhibited a high degree of coherence and stability, which allowed us to map out the orbital dynamics of a vortex dipole; (iii) finding that vortex dipoles could survive for many seconds in the BEC without self-annihilation, due to the oblate nature of the BEC; (iv) discovering the formation of multi-quantum vortex dipoles, new quantum states of BECs that have not previously been discussed in the literature, but that may play a role in future understanding of quantum turbulence in highly oblate quantum fluids.

Theory of Optical Refrigeration of Semiconductors and Nonlinear Optical Response of Quantum Well BRAGG Structures
PI: Rolf Binder

(4) Statement of the problem studied

There were two main thrusts in our JSOP project: (i) we studied optical refrigeration (sometimes called laser cooling) of semiconductors, and (ii) we studied optical nonlinearities and optical switching in semiconductor quantum well structures.

In (i) our goal was to develop a comprehensive theory of semiconductor laser cooling, which involves a predictive theory of photo-luminescence of highly excited semiconductors, a flexible theory for the cooling power, cooling efficiency and cooling threshold behavior, as well as a theory that permits modeling of structurally complex heterogeneous semiconductor systems. Our theoretical studies were coordinated with ongoing experimental studies at the University of New Mexico. The long term goal of this project is to build a new kind of integrated cooling system that works without moving parts and that has the capability to cool electronic and opto-electronic devices to cryogenic temperatures (ideally as low as 10 K).

In (ii), our goal was to analyze existing and ongoing all-optical switching experiments (mostly performed at the University of Iowa), and to develop new concepts for all-optical switching. A major aspect in the development of new concepts was the desire to propose a switching mechanism with very low switching power that work in a semiconductor (in other words solid state) environment. Both of these aspects (low power and solid state environment) are believed to be crucial for future generations of compact communication systems.

(5) Summary of the most important results

We successfully developed a comprehensive theoretical modeling tool that allowed us to analyze the semiconductor laser cooling experiments performed at the University of New Mexico, and to make specific proposals for improvements in future generations of experiments. The first very important result of our theoretical studies was the finding that the lack of experimentally observed cooling is not the consequence of one single prohibitive feature in the cooling system, but rather the cooperation of a number of small deficiencies in the systems presently used. The second important result is the finding (or prediction) that direct-gap semiconductors, such as GaAs, will indeed be able to achieve cryogenic temperatures in laser cooling operation, if the electronic resonance responsible for the cooling is chosen to be the lowest exciton resonance. One other words, for cooling to work at low temperatures, the Coulomb interaction between electrons and

holes is crucial. The third important result is a new proposal to achieve significant improvement of the non-radiative decay, which generally hinders optical refrigeration, through the use of highly-doped passivation layers (in our specific case the semiconductor is GaAs and the passivation layers are GaInP). This prediction is based on our simulations of the n-p-n structures and the realization that higher n-doping of the passivation layers reduce the minority carrier concentration at the GaAs/GaInP interface and thus interface non-radiative recombination.

The most important result in thrust (ii) is our proposal of a low-intensity all-optical switch based on semiconductor microcavities. We found that directional switching of light, in which weak light pulses switch strong light pulses, can be expected in high quality semiconductor microcavities, and we have proposed a specific geometry to achieve this (basically using a normal-incidence pump pulse detuned above the lower polariton branch with switching beams incident at specific angles that are dictated by the polariton dispersion). Our theoretical proposal for the low-intensity directional switch was published in Physica Status Solidi Rapid Research Letters and was featured on the cover of the January 2009 issue of that journal. In addition, a so-called Expert Opinion, written by M.C. Dawes and titled "Towards a single-photon all-optical transistor", introduced our paper and put it in the broader context of all-optical high-bandwidth communication networks.

High-brightness vertical-external-cavity surface-emitting lasers (VECSEL) and generation of visible lasers

PI: Mahmoud Fallahi

4) Statement of the Problem Studied:

High power laser sources in the visible range covering yellow-orange bands are of great interest for a wide range of applications including sodium guidestar laser, quantum computing, and medical applications [1-2]. Unfortunately there are no suitable direct band-gap semiconductor structures that can emit in a wide visible range, especially yellow-orange band. Despite these wide ranges of applications, the development of yellow-orange lasers has been very limited, mainly because it is hard to find active gain materials with transition in this band. Nonlinear frequency conversions have been frequently used to generate emission in the yellow-orange range. Several methods including frequency doubling of Yb solid-state lasers [3], frequencies doubling of Raman-shifted Yb (Nd) lasers [4], and frequency doubling of Bi-doped fiber lasers [5] have been investigated. Unfortunately majority of these approaches suffer from limited emission range, low output power and high cost. Development of a semiconductor- based high-power visible laser is very attractive. Strained multi-quantum well semiconductor lasers are widely used in the near IR range. However due to their limited direct band-gap energy, a range of visible emission wavelengths are hard to be directly fabricated. Optically pumped semiconductor vertical-external-cavity surface-emitting lasers (VECSELs) are very attractive to achieve high power, high brightness emission

unmatched by other semiconductor lasers. InGaAs/GaAs VECSELs are suitable active semiconductor material for the wavelength range of 900-1200 nm emission. Having access to the intra-cavity allows the development of high power frequency-doubled VECSELs in the 450-600 nm range. This report describes our study and results on high-power visible VECSELs development. We report our progress towards multi-watts cw blue-green and yellow-orange wavelength by frequency doubling of 980 nm and 1170 nm VECSELs respectively.

5) Summary of the Most Important Results:

Optically pumped vertical-external-cavity surface-emitting laser (VECSEL) using multi-quantum well semiconductors are very attractive for low-cost high-power high-brightness sources [6, 7]. In addition, by having access to the intra-cavity, several attractive features such as wavelength tuning, frequency doubling for visible generation and Q-switching can be achieved. In order to develop high-power frequency doubled visible lasers, two VECSEL structures, designed for emission around 980 nm and 1170 nm, were grown by metal-organic vapor phase epitaxy (MOVPE) on GaAs substrate. The active region consists of multiple InGaAs compressive strained quantum wells surrounded by GaAs barriers and GaAsP strain compensation layers. The thickness and compositions of the layers are optimized such that each quantum well is positioned at an antinode of the cavity standing wave to provide resonant periodic gain (RPG) in the active region. A high reflectivity (R > 99.5%) DBR stack made of 21-pairs of AlGaAs/AlAs is grown on the top of the active region. The challenges in the development of 1178 nm VECSEL (compared to 980 nm VECSEL) are highly compressive strain in the quantum well and waste heat in the active region due to the large wavelength difference between pump and signal.

The fabrication of the VECSEL of both 980 nm and 1170 nm VECSELs followed our standard processing steps previously reported [6]. The fabricated VECSEL should have high surface quality to minimize scattering/diffraction losses and efficient heat extraction from the active region to avoid thermal rollover and thermal lensing. To achieve this goal, a high thermal conductivity CVD diamond is used as the submount heat spreader. The fabrication process includes sample mounting and substrate removal. The substrate is first etched to a thickness of about 50 μm by a fast non-selective wet chemical etching. The remaining GaAs substrate is subsequently removed by selective wet chemical etching. The device was tested using our conventional VECSEL setup described previously. A concave external mirror with a reflectivity of ~96% is used as the external mirror. Figure 1 shows the output power vs input pump power performance of the VECSEL at ~ 1170 nm. Over 7 W is achieved for different heatsink temperatures.

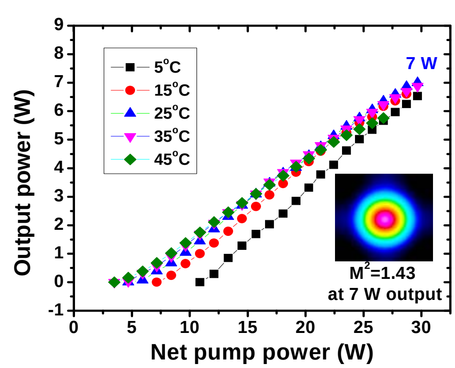
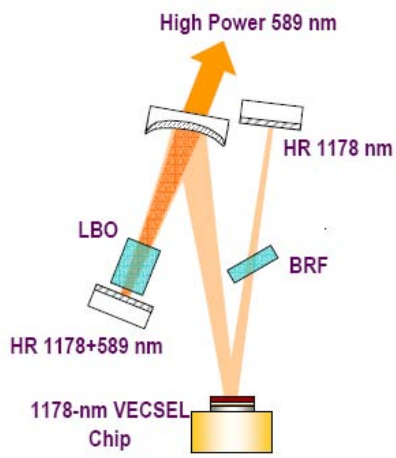
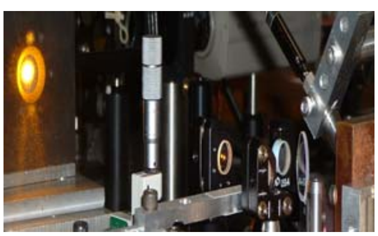


Figure 1. Measured CW output vs. pump power of a VECSEL and beam quality at 7W

To demonstrate high-power visible lasers, we used a folded cavity (see Figure 2) such that the mode size in the nonlinear crystal is small, increasing the intensity of fundamental laser inside the crystal. The cavity is high Q for the fundamental laser. The LBO crystal works as a doubler inside the VECSEL cavity. In the experiment, the LBO crystal is mounted in a metal holder without the temperature control, and the VECSEL chip is on a 25^{o} degree heatsink. Figure 3 shows the performance of the 589-nm yellow laser. Over 2 W of yellow under cw operation is routinely obtained. A yellow output as high as 5 W is recently achieved.





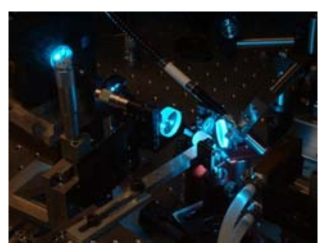


Figure 2. Cavity setup and visible VECSEL demonstration at 589-nm (yellow) and 488 nm (green) laser.

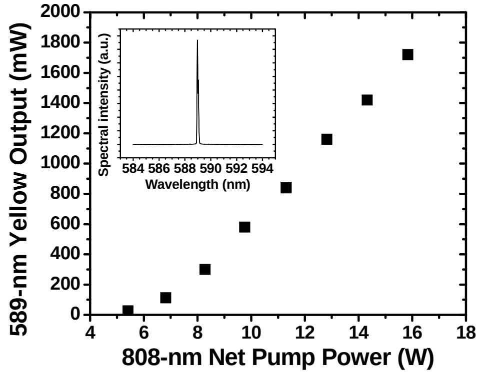
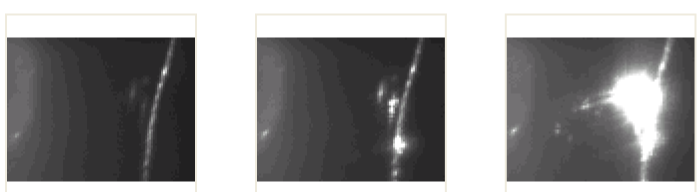


Figure 3. The performance of frequency doubled VECSEL at 589-nm.

Lateral Lasing Effect:
In order to power scale a Vertical External Cavity Surface Emitting Laser (VECSEL), the pump spot size can be increased. However, the large pump area greatly amplifies the guided spontaneous emission in the epitaxial plane. This Amplified spontaneous emission (ASE), in the worst case causing lateral lasing, results in the reduction of carriers from the active region, and limits the performance of the device. In an attempt to better understand and combat this problem we have developed a scheme for absorbing and releasing the spontaneous emission from the epitaxial plane.

Spontaneous emission naturally occurs at all angles inside the pump spot of the VECSEL. Because of the index guiding from the layer structure of the device, photons emitted in the epitaxial plane are unintentionally trapped by these guiding layers and amplified over the pump region. The large pump area of the VECSEL greatly increases the gain length in the lateral plane significantly amplifying the guided spontaneous emission. In addition, the quantum well gain is intrinsically temperature-dependent since the bandgap of semiconductor and the quasi-Fermi-Dirac distribution of the carriers are a function of temperature. As the temperature of the device is decreased the gain increases. This increase in gain also results in an increase in ASE and lateral lasing as we have previously seen and show in figure 4.



25C 15C 5C

Figure 4: Lateral lasing observation with sample cooling

There is one other aspect that greatly promotes lateral lasing. As the device is pumped, the active region begins to heat. This causes the optical resonance of the microcavity and

the quantum well gain peak to tune to longer wavelengths at the rate of ~ 0.1 nmK^{-1} and ~0.3 nmK^{-1}, respectively. The temperature in the surrounding material is then colder than the pumped area since the thermal flows in the device are primarily perpendicular to the surface. Because of this the band gap in the pumped region is less than that in the surrounding area. This results in the areas surrounding the pump spot to be transparent to the spontaneous emission. The mirrors provided by the edge of the VECSEL chip provide the feedback and ASE occurs. In the worst case, even though the edges of the chip are only around 30% reflective, the gain in the pumped region is high enough that a FP resonator is formed and lasing in the lateral plane occurs.

In a first experiment we attempted to quantify how much power is lost due to lateral lasing. To do this we found a device that exhibited intense lateral lasing, and tracked the lasing to the edge and intentionally burned the sample. This destroyed the lateral lasing by introducing a loss mechanism in the epitaxial plane. When we test the sample before and after the burning, we noticed the lasing threshold decreased the maximum output increased as shown in figure 5.   This was an effective method of reducing lateral lasing, but was difficult to implement and resulted in the destruction of many samples.

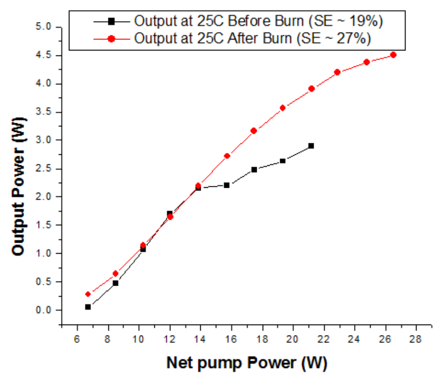


Figure 5: VECSEL output before and after intentional edge burn

In summary, we have studied and demonstrated high-power visible VECSEL in the green and yellow wavelength range. Green lasers with excess power of 1 W have been obtained by intra-cavity frequency doubling of 980 nm VECSELs. Yellow emission was obtained from highly-strained InGaAs/GaAs/GaAsP structure emitting at around 1170 nm. Intra-cavity frequency doubling of the 1170 nm lasers provided multi-watt of yellow-orange emission. The effect of amplified spontaneous emission and lateral lasing on the VECSEL performance were also investigated

Quantum Dots for Cavity QED Entanglement
PI's: Galina Khitrova and Hyatt Gibbs

4) Statement of the problem studied

Growth of quantum dots (QDs) for single quantum dot vacuum Rabi splitting in a photonic crystal slab nanocavity; optimization of the QDs for strong coupling and entanglement by controlling the dot density, transition wavelength, and size of the dipole moment via MBE growth parameters.

5) Summary of the most important results

We have grown many samples of InAs quantum dots for strong coupling to modes of photonic crystal slab nanocavities.[1,3,10,11-18,21,24] We have extended the wavelength range on GaAs substrates to 900-1300 nm and on InP substrates to 1400 nm. Some of the samples were grown just for QD characterization: dot density ρ, by atomic force microscopy (AFM); wavelengths, by photoluminescence (PL) spectra; and radiative lifetime τ (from which the dipole moment μ is calculated), by streak camera detection following fs above-band excitation. Some of the samples were grown with an AlGaAs sacrificial layer under a GaAs slab that contains the single layer of QDs in its center (and a top layer of QDs if AFM characterization was planned).The slab thickness d was extracted by broadband reflectivity measurements and transfer-matrix fits, taking advantage of the big difference in refractive indices of the GaAs and AlGaAs. Approximately 10 samples were grown on GaAs substrates to study the roughness at the top of the AlGaAs sacrificial layer. Approximately ten samples were grown to study the InAs QDs and to move the ensemble PL peak as close to 1200 nm as possible. About 10 complete structure samples (slab with dots in the center and an AlGaAs sacrificial layer underneath) were then grown. In addition about a dozen samples were grown to study InAs dot formation and the use of a GaAlInAs slab on top of an AlInAs sacrificial layer, both grown lattice-matched to the InP substrate. The nanocavity sample fabrication was performed by Uday Khankhoje, a graduate student in the group of Professor Axel Scherer, Caltech. We now have many GaAs/AlGaAs cavities with *Q* around 15,000, and one on QD58 is over 26,000. A principal conclusion of this systematic characterization of several dozens of samples is that it is difficult to obtain high *Q* for wavelengths shorter than 1100 nm, because of bulk and surface state absorption. Another is that AlGaAs roughness is not limiting *Q* at the present level of fabrication, since reducing it by an order of magnitude had little effect.

Two promising possibilities for the future are the GaAs/GaInP system and Si, both of which have been shown to have much higher *Q*s by other groups. Very recently we have achieved a *Q* of 70,000 using a Si nanobeam cavity in which total internal reflection provides optical confinement in two dimensions and a photonic crystal in the third.

In addition we grew 18 samples to study radiative coupling effects between QWs spaced, not periodically as usual, but instead with Fibonacci spacings. This still results in a photonic stopband, but with the addition of defect-like states within the stopband. Consequently, this Fibonacci 1D quasicrystal emits strong PL normal to the sample when the Bragg condition is satisfied. In contrast, a periodic 1D crystal has almost no PL under this condition. Several papers[4-6,9] and talks[19,20,22,23] resulted from studying the growth and the linear and nonlinear optical properties of such structures.

We have also grown a few samples to continue our collaboration on the physics of quantum dots with a former student of ours, Sangam Chatterjee, now at the University of Marburg.[2,7,8,25]

Near-Field Nonlinear Optics, Fiber Optics, Optical Limiting, and Solar Energy Conversion

PI: Alan Kost

4) Statement of the Problem Studied

Solar concentrators are often characterized by an acceptance angle. Typically, the acceptance angle is specified in the following way. The optical throughput for the concentrator (fraction of incident sunlight that is concentrated onto an active element such as a solar cell) is simulated or measured as a function of the angle between the

incident sunlight and the optical axis of the concentrator. The optical throughput is highest for an incident angle of zero degrees, remains high for a finite range of incident angles, and then decreases for angles larger than an “acceptance angle”. It can be shown that the maximum possible acceptance angle is given by

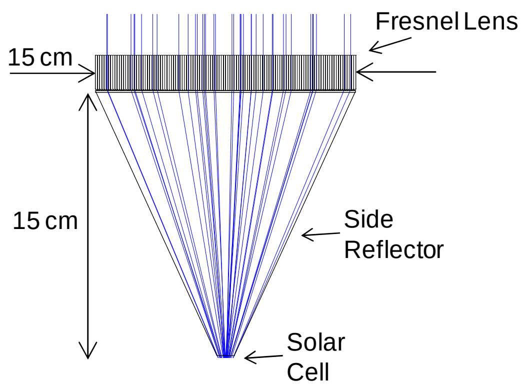
$$\theta_{\max} = \arcsin\left(\frac{1}{C}\right),$$

where C is the optical concentration [2].

Unfortunately, the acceptance angle does not tell the whole story. The illumination on an active element may be unacceptably non-uniform for angles less than the acceptance angle. For this effort we have performed simulations to illustrate this point and have developed the concept of an effective acceptance angle that takes into account the effect of the non-uniformity of illumination. We also examined “overfilled” optical concentrators that have large effective acceptance angles.

2. Acceptance Angle and Illumination Uniformity for a Conventional Concentrator

In order to illustrate the concept of an acceptance angle and its limitations we considered the solar concentrator pictured in Figure 8. A Fresnel lens concentrates sunlight 15 times (i.e. a medium concentration) onto a photovoltaic cell. Side reflectors increase optical throughput to the solar cell by guiding sunlight to the cell when the concentrator is misaligned. The acceptance angle is about 2.2 degrees – about half the theoretical maximum of 3.8 degrees.



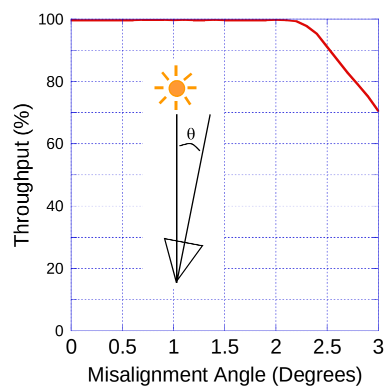


Figure 8. (Left) A 15x solar concentrator with a Fresnel lens to concentrate light on a solar cell and side reflectors to guide sunlight and increase acceptance angle. (Right) The fraction of incident sunlight that reaches the solar cell (throughput) as a function of the incident angle with respect to the optical axis of the concentrator (misalignment).

We have also simulated the illumination on the solar cell for the same concentrator misaligned by 1.0 and 1.5 degrees (Figure 9). A misalignment of 1.0 degrees produces an illumination that is dark on approximately half the solar cell and a peak concentration three times the design value of 15. A misalignment of 1.5 degrees results in a peak concentration more than four times the design value. These profiles could produce a substantial decrease in the optical-to-electrical conversion efficiency for the solar cell.

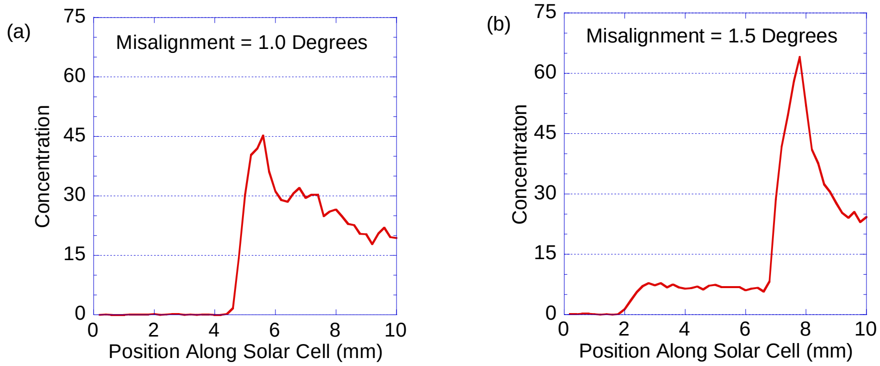


Figure 9. The simulated illumination on a solar cell at the base of a 15x solar concentrator misaligned by (a) 1.0 degrees and (b) 1.5 degrees.

3. Acceptance Angle and Illumination Uniformity for an Overfilled Concentrator

Next we considered the "overfilled" 15x solar concentrator pictured in Figure 10. By overfilled it is meant that the Fresnel lens directs a portion of the incident sunlight onto the side reflectors, even when the concentrator is perfectly aligned. The graph on the right hand side of Figure 10 shows that the acceptance angle of the overfilled version of the concentrator is just 1.2 degrees.

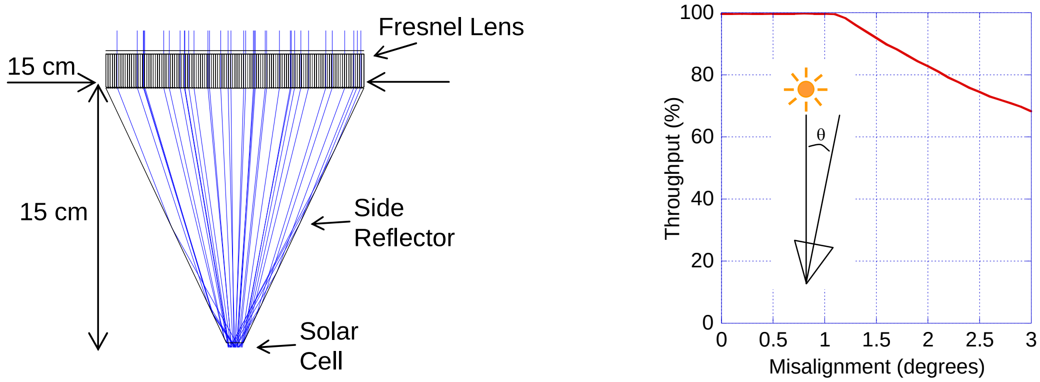


Figure 10. (Left) An overfilled 15x solar concentrator. (Right) The fraction of incident sunlight that reaches the solar cell (throughput) as a function of the incident angle with respect to the optical axis of the concentrator (misalignment).

If we judge concentrators on the basis of acceptance angle alone, we would have to conclude that the overfilled concentrator has inferior performance. However, consider the simulations of solar cell illumination in Figure 11. For the misalignment of 1.0 degrees there are no dark regions and the peak concentration is less than two times the design value of 15. Also note that the illumination for a misalignment of 1.5 degrees is considerably more uniform that for the corresponding conventional concentrator misaligned by the same amount. We see that the smaller acceptance angle for the overfilled solar concentrator is offset to a great extent by greater illumination uniformity on the solar cell.

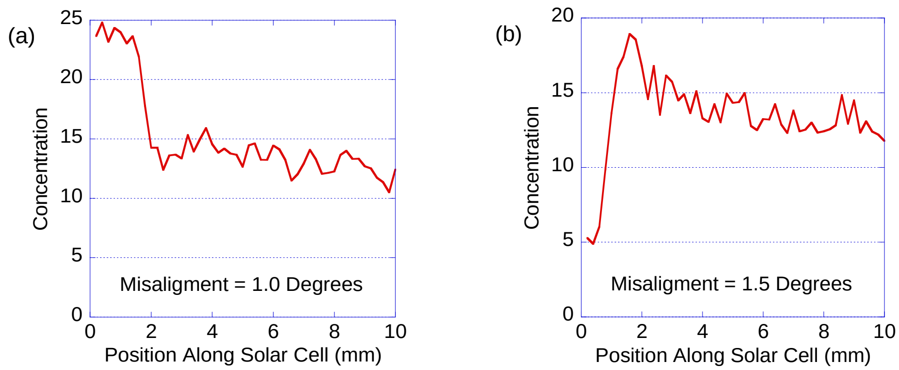


Figure 11. The simulated illumination on a solar cell of an overfilled 15x solar concentrator misaligned by (a) 1.0 degrees and (b) 1.5 degrees.

5) Summary of the most important results

An Effective Acceptance Angle

The results discussed above led us to conclude that it is desirable to define an effective acceptance angle that is derived from a combination of the optical throughput and the illumination uniformity. Certainly the amount of solar power that is converted to electrical power is limited by optical throughput. However, illumination non-uniformity can also reduce the electrical power produced because of reduced solar cell efficiency. The strategy for determining an effective acceptance angle is to multiply the optical throughput by a factor that represents the fraction of solar cell efficiency relative to its optimum value. The effective acceptance angle is the misalignment beyond which this product falls below an acceptable level (e.g. 90%).

Optically Bound Matter

PI: Prof. Ewan M. Wright

(4) Statement of the problem studied

This project has been focused on the problem of the self-organization of systems of nano-particles under the illumination of applied laser fields, so called optical binding of matter. The simplest example of optically bound matter involves binding of a few particles in the presence of one or two laser fields, the particles being formed into a bound state by the induced dipole-dipole interactions between the particles. At the other extreme one may consider the self-organization of a very large number of nano-particles in a colloidal suspension under the action of a laser beam, a system that has a large overlap with the nonlinear optics of colloidal suspensions. The problem studied during this project involved investigation of optically bound matter at both of these extremes with a view to obtaining a bigger picture of the physics and scope for optically bound matter. As part of this project I was fortunate to collaborate with Prof. Kishan Dholakia’s experimental group in St Andrews, Scotland, allowing for experimental testing of much of the theory developed.

(5) Summary of the most important results

For optical binding of a few particles the most significant results obtained are the development of a comprehensive model for optical binding that was thoroughly tested against experiment [1], use of these models to elucidate the physics underlying the optical binding of a few particles, and development of a theory and experiment to measure and verify the forces acting between optically bound particles [2]. This theoretical work provided a framework in which the physics of optical binding could be tested. Building on these successes we then explored optically bound matter for a very large number of nano-particles. In the first experiment we considered optically bound matter on a surface, and predicted the occurrence of solitons and modulational instabilities arising for colloidal suspensions [3]. This work highlighted the intimate relation between optically bound matter for many particles and the nonlinear optics of colloidal suspensions. In particular, they showed that the large scale organization of optically bound matter could be interpreted using concepts from nonlinear optics such as optical spatial solitons. Finally we explored the self-organization of optically bound matter in bulk colloidal suspensions and it's relation to nonlinear optical self-trapping [4]. In particular, this work led to the first theory experiment comparison of self-trapping in colloidal suspensions, and required a significant rewriting of the conventional theory of the nonlinearity of colloidal suspensions [5]. Specifically, we found that inclusion of particle-particle interactions is key to understanding optically bound matter in bulk media.

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